Thermo-Mechanical Tests Combining Thermal, Mechanical and Physical Measurements

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Abstract
Numerical models of many forming processes of metals rely on description of rheological characterization of the metallic alloys, which can turn very difficult at high temperature. In this work, a direct resistance heating machine (Taboo) has been developed to perform cyclic loadings at very low strain rates (10^{-3} and 10^{-4} s^{-1}) between 900°C and the solidus temperature. We first describe the experimental setup; then we present several measurement techniques. A specificity of resistance heating machines is to deal with non negligible temperature gradients around the center of the sample which induce heterogeneous strains. To measure displacements, a specific set-up has been constructed using speckle correlation. It has several advantages like full field and non destructive displacement measurement. Thanks to this method we obtain full field measurements. Electric current and resistivity measurements are also performed all along the heating/cooling and deformation stages. They can be correlated to phase transformation. Finally, we describe a numerical model for simulating and analysing the tests with a combined electrical, thermal and mechanical model. The main goal is to help designing optimal sample geometry using to identify mechanical parameters by inverse analysis.

Keywords: Mechanical tests, Speckle correlation, Temperature regulation

Introduction

The understanding of solidification crack phenomena is still a technological and industrial challenge. On the one hand, industrial concerns are considerable, in terms of quality and productivity. On the other hand, this is also a scientific challenge, because the physical mechanisms of hot tearing are far from being understood. The reason for this is that it is a highly metaphysics problem. One of challenges is the rheological characterization of alloys, which is particularly difficult at high temperature and in the semi-solid state. And actually, there are only few data for consecutive laws of industrial steel for solidification conditions (i.e high temperature and very law strain and strain rate). In this work, the rheological characterizations in solid and semi solid state are carried out using a direct resistance heating machine (Taboo) which allows cyclic loadings at very low strain rate (10^{-3} - 10^{-4} s^{-1}) between 900°C and the solidus temperature. A specificity of resistance heating machine relies in a high non thermal homogeneity in the central part of the sample. And this non thermal homogeneity produces a heterogeneous strain which has to be known for precise mechanical analyses. The speckle correlation photography has several advantages like full field and non destructive measurement, but this method is classically limited in temperature (around 900°C). Indeed to produce the speckle, a painting is commonly used and this does not stand high temperatures. And at high temperatures, these methods which are based on optical measurements are also very sensitive to the visible spectrum, particularly in the red wavelengths. All these limits lead to develop a new method based on laser produced speckles. A green laser can be used, since steel does not radiate in green wavelengths around 1500°C. In this work a technique is also presented to analyse pictures based on a cross spectrum method. This method proves more accurate than cross correlation for small displacement and more efficient to analyse quickly two pictures (in only few ms). In this paper, first we describe the experimental setup; then we present the measurement techniques. Thanks to these methods we obtain full field measurements. And finally, we describe a suitable numerical model: the tools and the samples are numerically modelled with a combined electrical, thermal and mechanical solver. The goal of this model in this study is simply to help understanding and visualising the temperature gradients and displacement fields throughout a sample.

State of the Art

Image correlation is a useful tool for measuring displacement field during mechanical testing; with such a method 2D displacement field can be deduced from recorded images (Sutton et al(1983)). Previous work on full field measurement a high temperature using optical methods is limited. Some developments and experiments are based on the lighting of a structured pattern (grid or lines) deposited on the surface of the sample (Sharpe et al (1997) or Pinna et al (2007)). The maximum temperature achieved for accurate strain measurement was around 700°C. More recently some papers deal about the full field measurement based on a lighting of the surface texture. The surface texture is used like a natural and random pattern (Grant et al (2009) or Pan et al (2011)). With such methods, authors are able to observe displacement fields for higher temperatures than 1000°C.

In the present study, we describe an optical method based on the lightening of the surface roughness with a green coherent light. The picture recorded during the mechanical test are analysed with a innovative hybrid method. When imaging surface roughness at high temperature a number of problems are met to measure a correct displacement field. Among all problems let us mention the two following ones :

- Black body radiation is increased when the temperature increases. The increase of light emission produces a decrease of the contrast on the recorded images. To avoid this radiation a classic way is to use a filter in a wave length where the radiation is the lowest, typically in the green or in the blue wavelength.

- The oxidation is another main problem because it causes changes in terms of surface texture. To avoid decorrelation problems an inert gas can be used to reduce oxidation. The advantage of using intrinsic surface contrast is also the ability of the method to record successive images. The time between two pictures is then usually short enough to avoid significant changes of the surface texture.

Experimental Setup

Taboo Tensile Test Machine. The "Taboo" machine is a thermo-mechanical simulator which has been developed at Cemef to investigate the behaviour of steels at very high temperature up to the solidus temperature and possibly in the semi-solid state (**Fig. 1**).

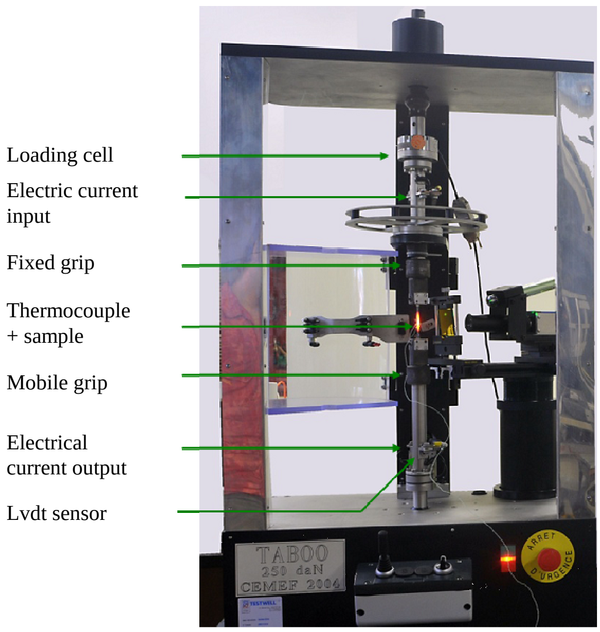

Figure 1. Taboo tensile test machine.

Before applying the loading cycle, the sample is directly heated by Joule effect using a continuous current. The temperature monitoring of the sample is achieved as follows. A thermocouple is welded in the middle of the specimen. During the heating and loading phases of the test, the current intensity is dynamically controlled in order to prescribe a desired temperature. An alternative monitoring procedure consists in using a thermal camera to measure the temperature field on the specimen surface. During the heating stage, the mobile grip displacement is monitored so that no external force is applied on the specimen. Once the desired temperature is reached, the mechanical test starts and the tensile force is measured by a load cell. The measurement of force versus displacement curves requires a high temperature extensometry technique. For that purpose, a non-contact method has been developed and is presented in the next section.

Laser Speckles Set-up (Fig. 2). A laser is projected on the area in which the displacement field needs to be measured. The laser beam is enlarged by a microscope lens that allows illuminating a large area on the central part of the tensile sample (typically 10 x 6 mm, the specimen being 90 mm long and 6 mm wide). Speckle images arising from local interference phenomena due to surface roughness are captured by a CCD camera and are simultaneously transferred to a computer. The size of analysed pattern areas is 1920 x 1080 (about 2 Mpixels). Each pixel can store a grey scale 8-bit value ranging from 0 to 255. During the experiment, a series of patterns can be either collected for post treatment later on or correlated and analysed for the control loop. The correlation between initial and current speckle patterns provides the displacement, as explained in the next section.

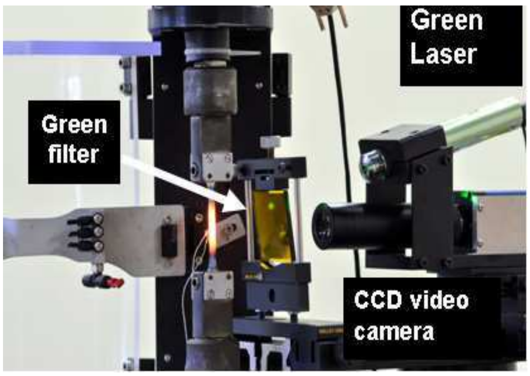

Figure 2. The laser speckle set-up

Image Correlation Techniques

The surface is considered to change relatively slowly during the experiment. Consequently, over a small time step, strains are low and the observed images are simply translated. In the following paragraph a technique of image analysis based on a coupled cross-correlation / cross-spectrum technique is presented. This technique is used to obtain the displacement field from two images. This coupled method allows characterizing the displacement within a few milliseconds with a sub-pixel resolution for a large range of displacement (from less than 1 pixel to 20 or more pixels).

The cross-spectrum and the cross-correlation methods have different advantages. Cross-correlation method is less accurate for small displacements and less rapid than cross-spectrum method but it is more accurate for large displacement.

The Cross-spectrum Method (Petrov et al. (1982), Aime (2001)). Consider a plane surface covered by a speckle pattern where the image intensity at time t_0 is defined by $f(x,y)$. The Fourier transform $F(u,v)$ is defined as:

$$TF\{f(x,y)\} = F(u,v) = \iint f(x,y) e^{-2i\pi(ux+vy)} dxdy \qquad (1)$$

Consider now a second image where the intensity at time $t_1 = t_0 + \Delta t$ is defined as $g(x,y)$. If function $g(x,y)$ is written as a translation of $f(x,y)$:

$$g(x,y) = f(x - x_0, y - y_0) \qquad (2)$$

and defining the cross-spectrum $I(u,v)$ as the multiplication of $F(u,v)$ by the complex conjugate of $G(u,v)$ (denoted $G^*(u,v)$), we get:

$$I(u,v) = F(u,v)G^*(u,v)$$

$$= F(u,v)F^*(u,v)e^{2i\pi(ux_0+vy_0)} = |F(u,v)|^2 e^{2i\pi(ux_0+vy_0)} \qquad (3)$$

Equation(3) shows that the displacement can be expressed according to two components corresponding to two different directions. The phase can consequently be decomposed into two expressions. The displacement is obtained from a linear fit of the expression of the phase **Fig.3 a)**. It seems quite simple to obtain a measure of the displacement between two different pictures with a cross-spectrum method. But, at high spatial frequencies, the noise and/or a bad sampling can lead to a zero value of the phase instead of showing the expected random variation (between -π and +π). Moreover, fitting the phase slopes is not precise when the displacement is larger than 1 pixel. In fact, in this case the phase varies between -π and +π. A displacement can not be accurately determined when a poor sampling is added to a slope of the phase, as illustrated in **Fig.3b**.

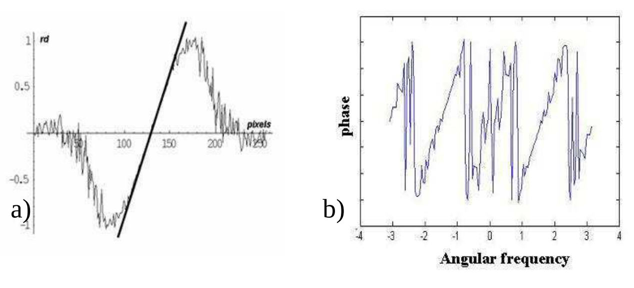

Figure 3. a) Example of displacement calculations. The phase falls down to 0 for high spatial frequencies; b) Example of the phase for a displacement larger than 1 pixel.

The Cross-correlation Method. In most papers dealing with field measurement (e.g. Chevalier et al (2001), and Huan et al (2007)), the cross-correlation technique is reported to be used. In practice, the Wienner-Kinchine theorem states that the cross-correlation can be written as the inverse Fourier transform of Equation (3) and these two functions contain equivalent information. However, it is more convenient to use the cross-spectrum method to measure very small displacements (smaller than pixel). Defining the Fourier transform of $I(u,v)$ as $I(\xi,\eta)$, we write:

$$I(\xi,\eta) = \iint I(u,v) e^{2i\pi(\xi u+\eta v)} dudv$$
$$\iint |F(u,v)|^2 e^{2i\pi(u(\xi-x_0)+v(\eta-y_0))} = \bar{I}(\xi - x_0, \eta - y_0) \qquad (4)$$

A Coupled Cross-correlation - Cross-spectrum Technique. As mentioned above and shown in **Fig. 4**, for a large displacement (over 10 pixels), the use of the cross-spectrum method becomes inappropriate. Moreover, a shear mode might be difficult to analyse. Indeed, a minor displacement in the non-longitudinal direction creates a noise for the phase in the principal direction. In this case, it is suggested to use a coupled cross-correlation - cross-spectrum technique (CC-CS). The principle of the method is presented in **Fig. 4.** As shown is this figure, a cross-correlation is first used to determine a displacement of the order of one pixel. One of the two images is shifted about one pixel and a cross-spectrum analysis is then used to determine the sub-pixel scale displacement.

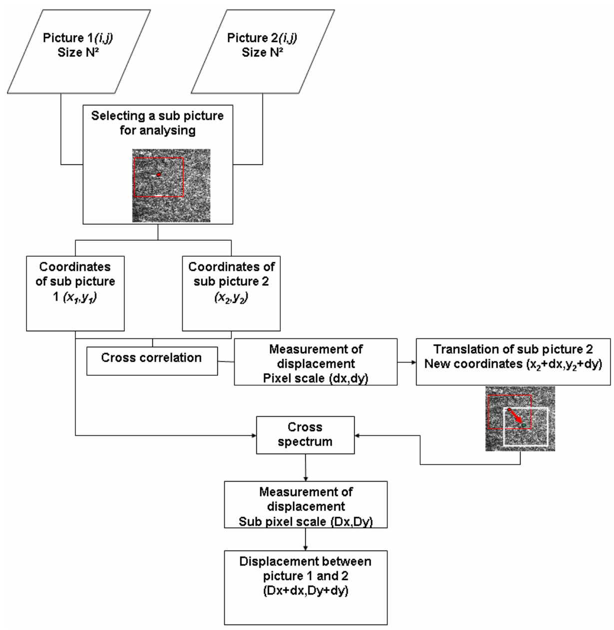

Figure 4. Schematic algorithm of the coupled cross-correlation cross-spectrum (CC-CS) technique.

Finally, displacement between two images is calculated by summing the displacements obtained by the two methods. In the technique presented here, a single image is divided into a grid of sub-pictures. Their size varies between 8x8 and 256x256 pixels. The algorithm is then applied to each couple of sub-pictures to determine the local displacement field between them. Therefore, the size and number of sub-pictures give the maximum spatial resolution of the displacement field. Sub-elements can be perfectly placed side-by-side or overlapped.

The numerical approach

In the thermo-mechanical tests which are performed, significant temperature and displacement gradients can be observed. To understand the origins of these gradients, a numerical model has been developed and used. A finite element model has been developed to simulate the entire experimental process (Favennec et al (2003)). This electrical, thermal and mechanical simulation of a tensile test which used direct resistance can be adapted to study multi-physics phenomena involved in such mechanical testing. This numerical model allowed to design optimal sample geometry and to minimise the temperature gradients throughout the samples. Indeed, for a subsequent analysis, it is preferable that the deformed area be as homogeneous as possible in terms of temperature. Then the numerical model is also able to simulate the complete tensile test including the heating with a temperature control by a PID.

Electrical-thermal problem. Once applied, the electric current generates heat in the conducting materials. As a consequence, the electrical potential and the temperature are strongly dependent, and two coupled problems are solved. The modeling is based on the charge conservation law, $\nabla \cdot \vec{J} = 0$, and the balanced energy equation. More precisely, applying Ohm's law:

$$\vec{J} = \sigma_e \vec{E} = -\sigma_e \nabla U \,, \qquad (5)$$

where $\vec{E} = -\nabla U$, the electric equation is written:

$$\nabla \cdot (\sigma_e \nabla U) = 0 \,, \qquad (6)$$

and knowing that the internal source of energy is produced by the heat generated from Joule effect, the heat source is written: $q_e = \vec{J} \cdot \vec{E}$. Considering $\Omega \subset IR^3$ the domain of calculations that covers the whole apparatus, the distribution of current and temperature is calculated by solving at each time step the two coupled three-dimensional partial differential equations:

$$\begin{cases} \nabla \cdot (\sigma_e \nabla U) = 0 & \text{on} \quad \Omega \\ \nabla \cdot (-k\nabla T) + \rho c_p \dfrac{dT}{dt} = \sigma_e \|\nabla U\|^2 & \text{on} \quad \Omega \\ + \text{Boundary conditions} & \end{cases} , \qquad (7)$$

where ρ is the density and Cp is the specific heat. The physical properties are dependent of the temperature and are implemented as functions of the temperature calculated at each step.

Experimental boundary conditions. The 3D experimental geometry was considered in the simulation of the electric-thermal coupled problems. To minimize heating rates in the grips, grips are water cooled. As a consequence, the heat losses of the two extreme upper and lower parts of the samples are presented by a conductive heat flux:

$$\phi_{cond} = h_{cond} (T - T_{grips}) \,, \qquad (8)$$

where $h_{cond} = 800\, W.m^{-2}.K^{-1}$ is the constant heat transfer coefficient, T the temperature of the boundary surfaces of the sample and T_{grips} the temperature of the grips. A coupled convective and radiative boundary condition is applied on the orther parts of the sample:

$$-k\vec{\nabla}T.\vec{n} = h(T - T_{ext}) + \varepsilon_r \sigma_s (T^4 - T_{ext}^4) \,, \qquad (9)$$

where $\sigma_B = 5{,}67.10^{-8}\, W.m^{-2}K^{-4}$ is the Stefan-Boltzmann's constant, ε_r the emissivity (assumed to be equal to 0.8 in this study), T the temperature of the boundary surfaces and T_{ext} the room temperature.

Temperature Control by PID Numerical Regulation. As it is mentioned in the first paragraph, during a Taboo test, the sample is heated by Joule effect, and should be maintained to a prescribed temperature. According to the boundary conditions, a zero potential is imposed on one surface, and an electrical current density is imposed on the other surface. La phrase précédente est à enlever : elle doit figurer dans le commentaire d'une figure présentant le cas. As it is made on the taboo machine, during a simulation the current density is continuously controlled by a PID algorithm according to the prescribed temperature. At each time, the injected current density J is calculated as a function of the errors between calculated and prescribed temperatures :

$$J^t = K_p \times error^t + K_i \sum_{t=0}^{t} error^t + K_d \times (error^t - error^{t-1}) \,, \qquad (10)$$

where K_p, K_i and K_d are the proportional, integral and derivative constants. The *error* is calculated as follows:

$$error = T_{prescribed} - T_{calc} \,, \qquad (11)$$

The calculated temperature is measured at a node located in the center on the sample surface

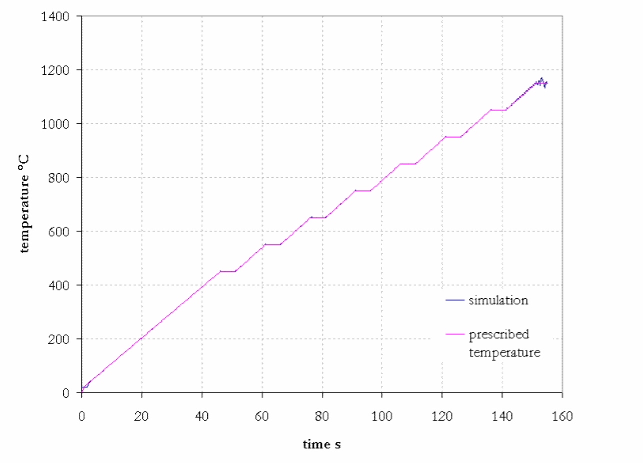

Figure 5. An example of PID temperature regulation.

Examples of temperature fields obtained with numerical simulations are shown in **Fig. 6** and **Fig. 7** for two different types of sample geometry.

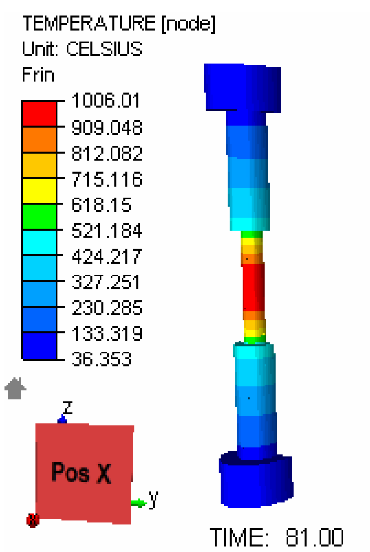

Figure 6. Temperature field (°C) along an axi-symetric sample.

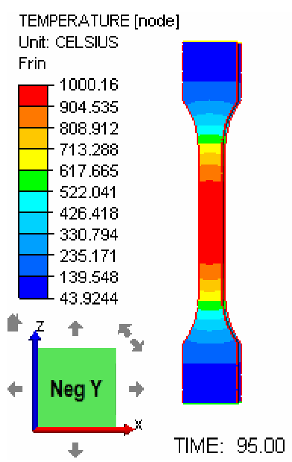

Figure 7. Temperature field (°C) along a flat sample

Analysis of an experimental case

Tests at high temperature have been performed using Taboo, a resistance heating device. As an example, a monotonic tensile test at 1200°C is presented. A constant ram speed of 0.05 mm/s is imposed over 20 seconds. During the test, the deformation is analysed in the whole central area which is depicted in **Fig. 8**. The frame shows a 10 mm long and 6 mm wide area, 6mm being in fact the width of the sample. Speckles are measured over this area are measured and analysed to provide the displacement and deformation fields. Interestingly, material points (dots shown in **Fig. 8**) serve as reference points for a virtual extensometer.

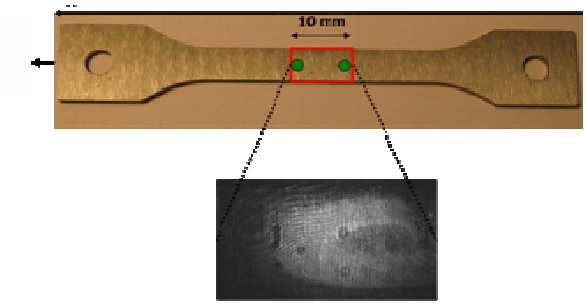

Figure 8. The frame shows the area over which the field analysis is performed. The two dots show the reference points for the “virtual extensometer”. Speckles during a test at 1200°C are also shown.

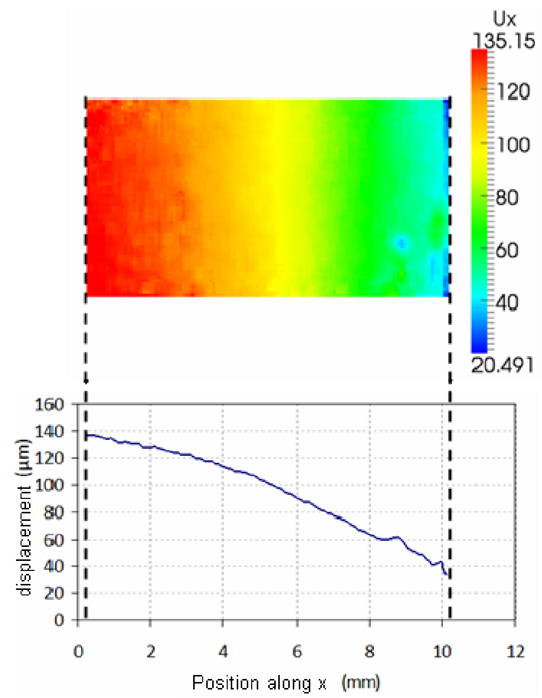

Figure 9. Displacement field which is measured in the central area of a tensile test sample at 1200°C after 3 seconds.

This way, local displacements similar to those measured using a real mechanical extensometer can be obtained. Complete displacement maps can also be recorded all along the test, as shown in **Fig. 9**, even for small strains.

After 3 seconds, the accumulated ram motion is only 150 µm. The extension of the control surface is 105 µm, which means that, even with a temperature gradient, the sample also deforms outside this central control surface. The measurements using the speckles analysis in the central area reveal that the deformation ranges from $\varepsilon min=0.005$ to $\varepsilon max=0.015$. Therefore, assuming that all the deformation takes place in the central area would lead to a large error (0.015 versus 0.0105). To better understand this strain gradient, the temperature field is simulated in a 30 mm area around the center of the sample (**Fig. 10**).

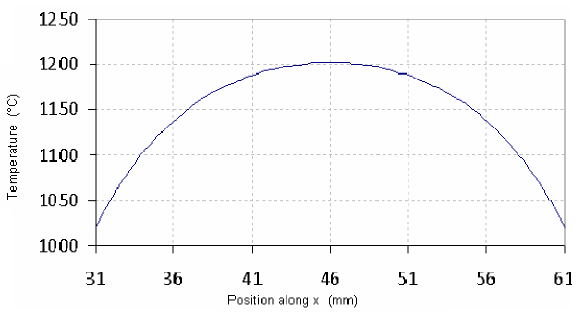

Figure 10. Numerical simulation of the longitudinal temperature profile in a 30mm zone around the center of the sample.

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Conclusion

A novel combination of experimental techniques is presented. The goal is to tackle the issues of characterising metals at high temperatures in conditions which are representative of industrial processes such as ingot or continuous casting, or high temperature solid state forming operations. A mechanical test set-up based on resistance heating is associated with a continuous measurement system using laser speckles. This system provides information which can be analysed with an image correlation technique to produce displacement fields and strain fields. Given the temperature gradients and the induced strain gradient in the center of the sample, this complete measurement of the strain field is needed to validate the test and derive precise rheological data. A numerical simulation model has also been developed to integrate coupled electrical, thermal and mechanical features of the test. On-going work consists in deriving the parameters of various constitutive laws from such measurements using an inverse analysis approach. It could also help optimizing the sample geometry.

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